MEASUREMENT OF GAUGE BOSON COUPLINGS AND W SPIN DENSITY MATRIX AT LEP

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During the LEP2 period the e^+e^- collider increased its center of mass energy from 161 GeV to 209 GeV and a total integrated luminosity of approximately 700 pb^{-1} was recorded per experiment. Pairs of W bosons are produced and allow the study of gauge boson couplings involving W, Z and photon. The coupling of the W boson to the neutral gauge bosons have been measured to be $g_1^Z = 0.998^{+.023}_{-.025}$, $\kappa_\gamma = 0.943^{+.055}_{-.055}$, and $\lambda_\gamma = -0.020^{+.024}_{-.024}$ and are in agreement with the Standard Model expectation. Limits are set on CP-violating couplings by a Spin Density Matrix analysis of the W decay products. No evidence has been found for couplings of three neutral gauge bosons, parametrized by $f_{4,5}^{Z,\gamma}$ and $h_{1,2,3,4}^{Z,\gamma}$. Limits are derived on couplings of four gauge bosons, parametrized by $a_0^{Z,W}/\Lambda^2$, a_n^W/Λ^2 and $a_c^{Z,W}/\Lambda^2$ where Λ represents the energy scale for new physics.

1 Gauge Boson Couplings

At LEP2, data are collected at center of mass energies ranging from 161 GeV up to 209 GeV. Massive W bosons are produced in pairs via e^+e^- interactions and gauge couplings involving W, Z and photon are studied by the four LEP experiments ALEPH, DELPHI, L3 and OPAL [1].

The non-Abelian $SU(2)_L \otimes U(1)_Y$ gauge symmetry of the Standard Model [2] predicts tree level interactions between three or four charged and neutral gauge bosons called triple and quartic gauge couplings. At LEP2 energies, triple gauge couplings are directly observed while quartic gauge couplings are negligible. Interactions between neutral gauge bosons do not exist in the Standard Model.

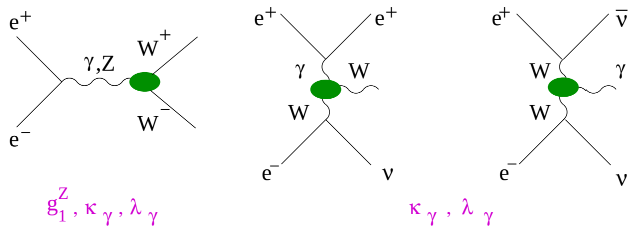

Figure 1: The processes sensitive to ZWW and γWW triple gauge couplings : W-pair, single W and single photon production.

2 Triple Gauge Boson Couplings

The most general Lorentz invariant Lagrangian involving WWV ($V = \gamma, Z$) vertices can be parametrized by 14 real parameters [3]

$$i\,\mathcal{L}^{WWV}/\,g_{WWV} = g_1^V V^\mu (W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} \tag{1}$$

$$+ \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} + i g_5^V \epsilon_{\mu\nu\rho\sigma}[(\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})]V^\sigma$$

$$+ i g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu - \partial^\nu V^\mu) - \frac{\tilde\kappa_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde\lambda_V}{2M_V^2} \mathrm{W}^-_{\rho\mu}\mathrm{W}^{+\mu}_\nu \epsilon^{\nu\rho\alpha\beta}\mathrm{V}_{\alpha\beta}$$

where g_1^V, κ_V, λ_V and g_5^V are CP-conserving couplings while g_4^V, $\tilde\kappa_V$ and $\tilde\lambda_V$ are CP-violating. Assumming CP-conservation and electromagnetic gauge invariance, five parameters are left : g_1^Z, κ_Z, κ_γ, λ_Z and λ_γ. The custodial $SU(2)$ symmetry of the Lagrangian imposes the constraints

$$\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W \qquad\qquad \lambda_\gamma = \lambda_Z \tag{2}$$

where θ_W is the weak mixing angle. Three free parameters are left : g_1^Z, κ_γ and λ_γ. They are related to the magnetic dipole and electric quadrupole moment of the W. The Standard Model predicts their values to be $g_1^Z = \kappa_\gamma = 1$ and $\lambda_\gamma = 0$ at tree level.

The triple gauge couplings are studied in W-pair production, sensitive to all three parameters, and single W and single photon production which are sensitive to κ_γ and λ_γ only. The corresponding Feynman diagrams are presented in Figure 1. Only results from W-pair and single W production are used at present for LEP combination.

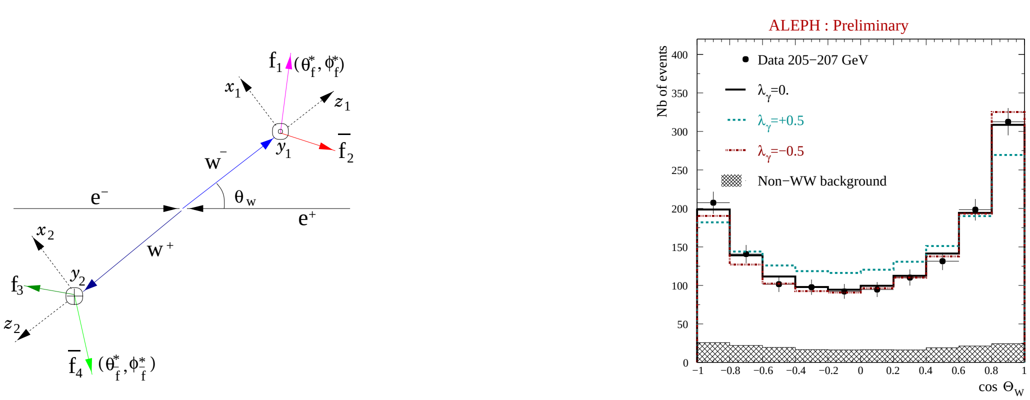

Figure 2: Left : The definition of the angles used in the coupling extraction Right : W production angle measured by the ALEPH experiment in fully hadronic W-pair events.

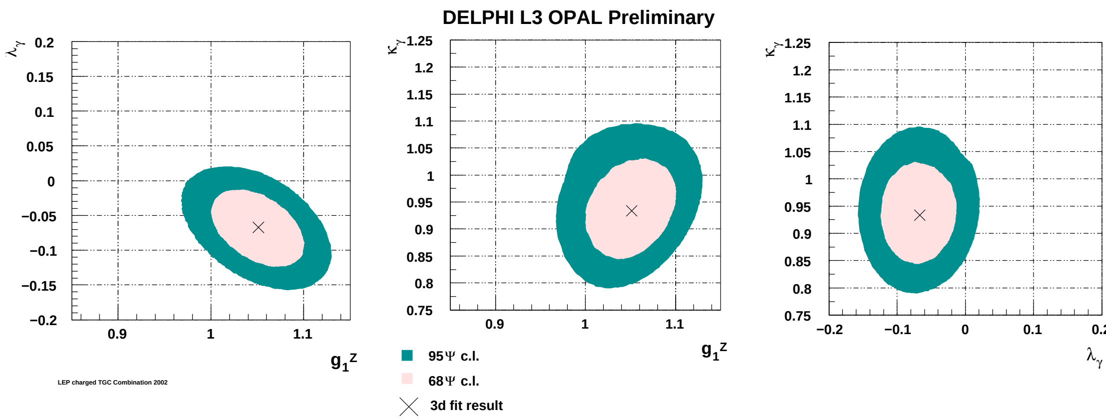

Figure 3: The result of the three-parameter fit, plotted in two-dimensional planes defined by the three TGC pairs. The third parameter is at its fitted value.

Table 1: The sources of experiment correlated systematic uncertainties in the LEP combination and their effect on the combined fit results.

Source	g_1^Z	λ_γ	κ_γ
$\mathcal{O}(\alpha)$ corrections	0.015	0.015	0.039
Hadronisation	0.004	0.002	0.004
Bose-Einstein correlation	0.005	0.004	0.009
Colour Reconnection	0.005	0.004	0.010
σ_{WW} prediction	0.003	0.005	0.014
$\sigma_{single\ W}$ prediction			0.011

A deviation from a coupling value predicted by the Standard Model would modify the total cross section, the shape of the W production angle θ_W, the polar angle $\theta_f^\star$ and azimuthal angle, $\phi_f^\star$ of the W-decay fermions in the corresponding W rest frame. These angles are presented in Figure 2 together with the distribution of the W production angle as measured by the ALEPH experiment in fully hadronic W-pair events. The expected distribution in presence of an anomalous coupling $\lambda_\gamma = \pm 0.5$ is also indicated.

The couplings are extracted by a maximum likelihood fit to the angular distributions (DELPHI, L3) or by a χ^2-fit to Optimal Observables distributions (ALEPH, OPAL). The results from each LEP experiment are then combined using a log-likelihood method [1,4].

The result from the three-parameter fit, including LEP2 data from DELPHI, L3 and OPAL, is presented in Figure 3. The LEP combined one-parameter fit results [1]

$$g_1^Z = 0.998^{+.023}_{-.025} \qquad \kappa_\gamma = 0.943^{+.055}_{-.055} \qquad \lambda_\gamma = -0.020^{+.024}_{-.024}\ .$$

are in agreement with the Standard Model prediction. The quoted errors include both statistical and systematic uncertainties. In the LEP combination all W decay channels were used except the semi-leptonic channel for L3 and LEP2 data from $\sqrt{s} = 189$ GeV on for DELPHI.

The correlated systematic uncertainties in the combined fit results are presented in Table 1. The largest contribution comes from the $\mathcal{O}(\alpha)$ radiative corrections, mainly due to virtual radiative corrections between the W bosons and the initial and final state particles. The effect is taken into account by Monte Carlo generators as YFSWW3 [5] in the Leading Pole Approximation (LPA) and RacoonWW [6] in the Double Pole Approximation (DPA) and introduces a 0.7 % uncertainty on the slope of the $\cos\theta_W$ distribution. Up to now the full difference between the Monte Carlo prediction with and without $\mathcal{O}(\alpha)$ radiative corrections is taken as a systematic

Table 2: The LEP combined one-dimensional limits at 95 % confidence level for the neutral triple gauge couplings.

95% CL	$V = Z$	$V = \gamma$
f_4^V	[-.31 ; .28]	[-.17 ; .19]
f_5^V	[-.36 ; .39]	[-.36 ; .40]
h_1^V	[-.13 ; .13]	[-.06 ; .06]
h_2^V	[-.08 ; .07]	[-.05 ; .03]
h_3^V	[-.20 ; .07]	[-.05 ; -.01]
h_4^V	[-.05 ; .12]	[-.002 ; .034]

uncertainty. Studies are still going on in the LEP experiments to define a more realistic estimate of the $\mathcal{O}(\alpha)$ uncertainty. An update on the TGC fits is planned for summer 2003.

Neutral triple gauge couplings do not exist in the Standard Model. The most general Lorentz invariant Lagrangian [3,8] for the VVZ ($V = \gamma, Z$) vertex is described by 12 parameters. The couplings h_1^V, h_2^V, h_3^V and h_4^V are studied at LEP in the $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma$ production, while f_4^V and f_5^V are accessible in $\mathrm{e^+e^-} \rightarrow \mathrm{ZZ}$ production. Electromagnetic gauge invariance and Bose symmetry for final states with identical bosons are imposed. The couplings are determined from the angular distributions of the decay products and the total cross section. No evidence for anomalous h- and f- couplings has been found. The LEP combined one-dimensional limits at 95 % confidence level are[1,4] summarized in Table 2. Both statistical and systematic uncertainties are included.

3 *W* Spin Density Matrix

The Spin Density Matrix (SDM) method[7] has been introduced to study the W polarisation and is also used to set direct limits on CP-violating couplings, absent in the Standard Model.

Considering the helicity, the W-pair production process is written as

$$\mathrm{e}^+(\lambda')\ \mathrm{e}^-(\lambda) \rightarrow \mathrm{W}^+(\tau_2)\ \mathrm{W}^-(\tau_1)\ , \tag{3}$$

where λ (λ') $= \pm 1/2$ represents the helicity of the electron (positron). The helicities of the W^- and the W^+, denoted by τ_1 and τ_2 respectively, take the value $\tau = \pm 1$ for transversely polarised W bosons and the value $\tau = 0$ for W bosons with a longitudinal polarisation.

The two-particle joint SDM elements are then defined as[9,10]

$$\rho_{\tau_1 \tau_1' \tau_2 \tau_2'}(s, \cos\theta_W) \equiv \frac{\sum_\lambda F^\lambda_{\tau_1\tau_2}\ (F^\lambda_{\tau_1'\tau_2'})^\star}{\sum_{\lambda,\tau_1,\tau_2} |F^\lambda_{\tau_1\tau_2}|^2}\ , \tag{4}$$

where s is the center of mass energy and $F^\lambda_{\tau_1\tau_2}$ is the helicity amplitude for the production of a W pair with helicities τ_1 and τ_2. The single particle SDM elements are obtained by summation over all possible helicities of one of the W's

$$\rho^{\mathrm{W}^-}_{\tau_1\tau_1'}(s, \cos\theta_{\mathrm{W}^-}) \equiv \sum_{\tau_2} \rho_{\tau_1\tau_1'\tau_2\tau_2}(s, \cos\theta_{\mathrm{W}^-})\ . \tag{5}$$

The SDM elements are constrained by Hermiticity and their diagonal terms are normalised to unity $\sum_\tau \rho^{\mathrm{W}^-}_{\tau\tau} = 1$. The diagonal elements of the SDM matrix are real and express the probability to produce a W^- with helicity τ_1. The off-diagonal elements are complex and provide a test of CP-violation.

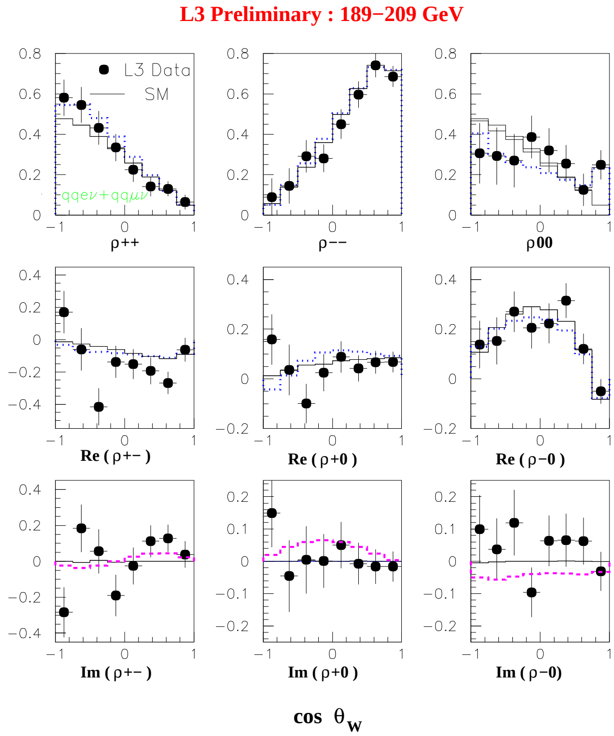

Figure 4: The nine single SDM elements, $\rho^{\mathrm{W}^-}_{\tau\tau'}$, as a function of $\cos\theta_{\mathrm{W}^-}$. The errors are statistical only.

The SDM elements are calculated in bins of $\cos\theta_{\mathrm{W}^-}$ using a projection operator method [9] assuming a V-A decay of the W boson into fermions

$$\rho^{\mathrm{W}^-}_{\tau\tau'}(k) = \frac{1}{N_k}\sum_{i=1}^{N_k}\Lambda^{\mathrm{W}^-}_{\tau\tau'}(\theta^\star_f,\phi^\star_f)_i \;, \tag{6}$$

where N_k is the number of events in the k-th bin and where the projection operator $\Lambda^{\mathrm{W}^-}_{\tau\tau'}$ is applied event by event. The reconstructed SDM elements need to be corrected for detector acceptance, resolution effects and background contamination for a direct comparison with the theoretical expectation.

The SDM elements measured by L3 [11] in the decay channels $q\bar{q}e\nu_e$ and the $q\bar{q}\mu\nu_\mu$ at $\sqrt{s} = 189 - 209$ GeV are combined and presented in Figure 4. The measurements for the leptonically decaying W^+ and W^- are combined assuming CPT-invariance. A good agreement is found with the Standard Model prediction represented by the solid line. The expected distributions in presence of an anomalous CP-conserving coupling $\Delta\kappa_\gamma = +0.5$ (dotted line) and the CP-violating coupling $\tilde{\lambda}_Z = -0.5$ (dashed line) are also shown.

The imaginary parts of the off-diagonal elements are insensitive to CP-conserving couplings and only contribute in presence of tree level CP-violation. This makes the SDM method particularly suitable to measure CP-violating couplings which are extracted by a χ^2-fit to the nine SDM-element distributions. As the $\cos\theta_W$ information is averaged out in the definition of the SDM elements, the shape of the W production angle is incorporated in the fit to increase the sensitivity. The following results are obtained by the OPAL [12] experiment with the $q\bar{q}l\nu_l$ events selected at 189 GeV

$$g_4^Z = -0.01^{+.32}_{-.33} \qquad \tilde{\kappa}_\gamma = -0.18^{+.24}_{-.16} \qquad \tilde{\lambda}_\gamma = -0.20^{+.10}_{-.07}\ .$$

All couplings are set to their Standard Model value except the measured one and these related to it by custodial $SU(2)$ symmetry. Both statistical and systematic uncertainties are included.

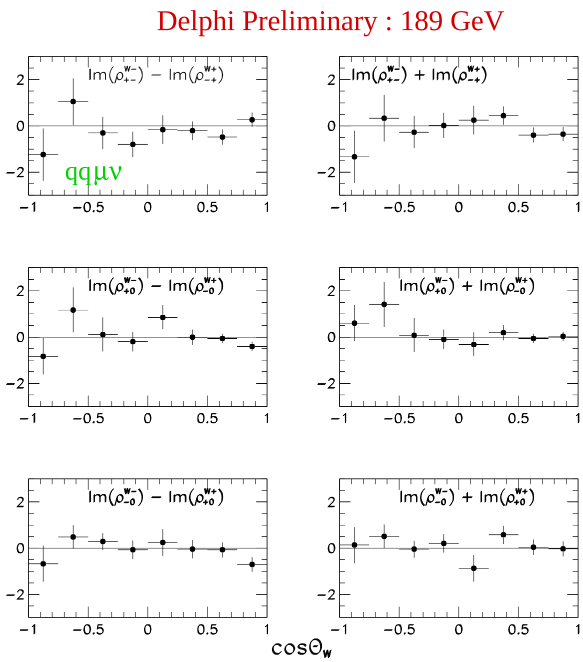

Figure 5: The sum of the imaginary parts of the off-diagonal elements, sensitive to CPT-violation at tree level (left), and the difference, sensitive to CP-violation at tree level (right). The errors are statistical only.

In the Standard Model W-pair production is assumed to be a CPT- and CP- invariant process, hence the following relations are satisfied

$$\mathrm{CPT-invariance}: \mathcal{I}\mathrm{m}(\rho^{\mathrm{W}^-}_{\tau\tau'}) + \mathcal{I}\mathrm{m}(\rho^{\mathrm{W}^+}_{-\tau-\tau'}) = 0 \tag{7}$$

$$\mathrm{CP-invariance}: \mathcal{I}\mathrm{m}(\rho^{\mathrm{W}^-}_{\tau\tau'}) - \mathcal{I}\mathrm{m}(\rho^{\mathrm{W}^+}_{-\tau-\tau'}) = 0 \tag{8}$$

The imaginary part of all SDM elements has to be zero and deviations from equation (8) provide an unambiguous signature for CP-violation at tree level. Deviations from equation (7) would arise from loop effects beyond tree level or CPT-violation. Figure 5 shows the test of CPT-invariance (right) and CP-invariance (left) measured with $q\bar{q}\mu\nu_\mu$ events selected by DELPHI [13] at $\sqrt{s}$ = 189 GeV. Within the statistical error, the sum, as well as the differences, of the imaginary parts are compatible with zero and confirm the absence of CPT- and CP-violation at tree level as predicted by the Standard Model (solid line). This is confirmed by the L3 [11] and OPAL [12] results.

In DELPHI and OPAL, the SDM analysis is also used to measure the cross sections for the production of transversely and longitudinally polarised W bosons which are a consequence of the spontaneous symmetry breaking mechanism in the Standard Model. The fraction of longitudinally polarised W bosons measured by OPAL at 189 GeV in the $q\bar{q}l\nu$ channel is $\sigma_L/\sigma_{total} = 21.0 \pm 3.3 \pm 1.6$ % where the first error is statistical and the second systematic. This is in agreement with the Standard Model expectation of 25.7%.

In L3 [14], the W polarisation is measured by a direct fit of analytical helicity distributions to the shape of the polar angle $\theta^\star_f$ of the W decay products in semi-leptonic W pair events. The W helicity fractions are presented in Figure 6 in four different bins of $\cos\theta_{\mathrm{W}^-}$. The fraction of longitudinally polarised W bosons measured with the L3 detector using $q\bar{q}l\nu$ events at $\sqrt{s} = 183 - 209$ GeV is $21.8 \pm 2.7 \pm 1.6\%$ and in agreement with the Standard Model expectation of 24.1%. Separate analyses of the W^+ and W^- events are consistent with CP-conservation.

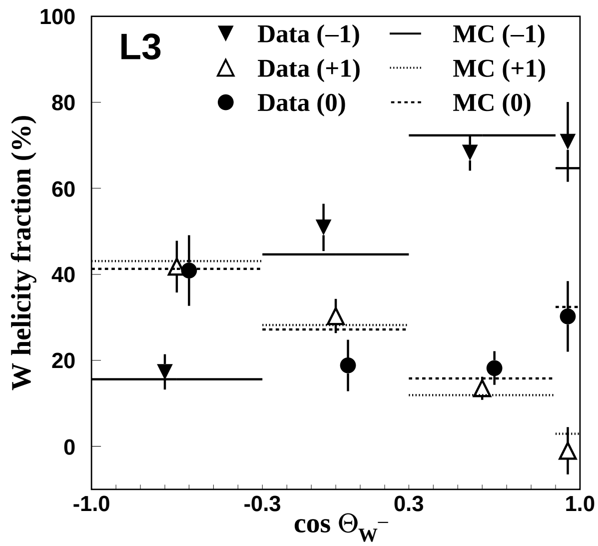

Figure 6: The W helicity fractions in four different bins of $\cos\theta_{\mathrm{W}^-}$ measured with the L3 detector using $q\bar{q}l\nu$ events at $\sqrt{s} = 183 - 209$ GeV compared to the Standard Model predictions from the KORALW Monte Carlo[15].

Table 3: The one-dimensional limits on quartic gauge couplings set by DELPHI, L3 and OPAL at 95 % CL.

95 % CL (GeV^{-2})	a_0^W/Λ^2	a_c^W/Λ^2	a_n^W/Λ^2
DELPHI	[-.018 ; +.018]	[-.057 ; +.030]	[-.16 ; +.12]
L3	[-.015 ; +.015]	[-.048 ; +.026]	[-.14 ; +.13]
OPAL	[-.054 ; +.052]	[-.15 ; +.14]	[-.61; +.57]

4 Quartic Gauge Couplings

The Standard Model quartic gauge couplings contribution are too small to be seen at LEP and any deviation is therefore a hint for new physics. Deviations are introduced into the Lagrangian [16,17] as effective couplings at a new physics scale Λ.

Starting from electromagnetic gauge invariance and custodial $SU(2)$ symmetry, the most general Lorentz invariant Lagrangian has 5 parameters. The quartic gauge couplings a_0^W/Λ^2, a_n^W/Λ^2 and a_c^W/Λ^2 are studied in the $\mathrm{e^+e^-} \rightarrow \mathrm{W^+W^-}\gamma$ process and in W fusion into a final state with two photons and missing energy due to the emission of two neutrino's, while the neutral quartic gauge couplings a_0^Z/Λ^2 and a_c^Z/Λ^2, not existent in the Standard Model, are searched for in the $\mathrm{e^+e^-} \rightarrow \mathrm{ZZ}\gamma$ process. Both are mainly determined from the photon energy spectrum and the total cross section.

No evidence for anomalous quartic gauge couplings has been found. The one-dimensional limits on quartic gauge couplings set by DELPHI [18], L3 [19] and OPAL [20] at 95 % confidence level are summarized in Table 3. Both statistical and systematic uncertainties are included. The one-dimensional limits on neutral quartic gauge couplings set by L3 and OPAL at 95 % confidence level are [1]

$$-.009 \ < a_0^Z/\Lambda^2 \ .\ \mathrm{GeV}^2 < \ .026 \quad -.033 \ < a_c^Z/\Lambda^2 \ .\ \mathrm{GeV}^2 < \ .046$$

New results from ALEPH [21] yield

$$-.011 \; < a_0^Z/\Lambda^2 \; . \; \mathrm{GeV}^2 < \; .017 \quad -.037 \; < a_c^Z/\Lambda^2 \; . \; \mathrm{GeV}^2 < \; .040$$

at 95 % confidence. Both statistical and systematic uncertainties are included. A LEP combination of the quartic gauge couplings is expected soon.

Acknowledgments

I wish to express my gratitude to my collegues from LEP and convenors of the LEP gauge coupling working groups for their support and discussions.

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